DIRECT-TO-EARTH COMMUNICATIONS FOR OUTER PLANETARY ENTRY PROBE MISSIONS

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David H. Atkinson [(1)], Kamal Oudrhiri, Thomas R. Spilker, Kevin H. Baines, Sami Asmar[(2)], Bernie Bienstock, Steve Sichi [(3)]

[(1)] Dept. of Electrical and Computer Engineering, University of Idaho, Moscow ID 83844-1023, USA, email: atkinson@ece.uidaho.edu
[(2)] NASA/Jet Propulsion Laboratory 4800 Oak Grove Dr., Pasadena, CA 91109-8099,USA
[(3)] Boeing Satellite Systems, P.O. Box 92919, Los Angeles CA 90009-2919,USA

ABSTRACT

The giant planets represent time capsules of the solar system, each reflecting the different chemical and physical conditions existing at the epoch and location of formation. In particular, the record of the past is locked in the makeup of key diagnostic constituents, including (1) the noble gases and their isotopes, which can not be measured remotely, and (2) condensibles such as water and ammonia, which are largely hidden beneath the clouds that form in the colder reaches of the upper atmosphere. Descent probes carrying the appropriate sampling instrumentation are fundamental for assessing the requisite inventories noble gas and condensible of giant planets necessary to constrain theories of solar system origin and evolution. Although not currently feasible to conduct *in situ* exploration of the deepest (100's of bars and deeper) outer planetary atmospheres, significant science can still be obtained from shallow descent probes that reach levels no deeper than several tens of bars. One method proposed for *in situ* studies of the shallow to middle levels of outer planet atmospheres (0.01 to several tens of bars) incorporates Direct-to-Earth (DTE) communications from shallow probes. Although the DTE technique does not require a communications relay option in a carrier spacecraft, thereby significantly decreasing overall mission cost and operational complexity, this technique involves a number of mission design risks that nevertheless could increase overall mission risk and severely impact the science return.

1. INTRODUCTION

1.1 Overview

To understand the origin and evolution of planetary atmospheres and interiors requires the composition of the atmosphere be known. Remote sensing of planetary atmospheres can provide valuable information on atmospheric dynamics, meteorology, global circulation, and chemistry, in some cases reaching levels well below the visible cloud tops. However, to completely address questions regarding the origin, evolution, and processes of the giant planets and solar system, *in situ* studies are often necessary and, in some cases, the only means by which the deeper atmosphere can be studied [1].

Direct sampling of deep planetary atmospheres requires that a probe, instruments, and sensors be able to survive the pressure and temperature environment of the atmosphere, and be capable of returning the acquired data to Earth. Although not technologically feasible for a probe to survive to and return data from the deep (100's of bars and deeper) atmospheres of the outer planets, significant science remains within the realm of relatively shallow descent probes [2]. To return science data from a descending probe, two strategies are considered: 1) the use of a second spacecraft as a relay station to receive, store, and later transmit the probe science data to Earth, and 2) the implementation of Direct-To-Earth (DTE) communications between a probe and Earth antennas. The advantages of DTE communications are obvious - simplification of certain aspects of two spacecraft (probe and relay spacecraft) mission, simplification of the communications system with one less in-space communications link, and overall reduction of mission costs. However, the technique of DTE communications may severely impact mission design considerations, limit the total science return, and substantially increase overall risk.

1.2 Giant Planet Science and Measurement Objectives

The outer solar system, comprising the four giant planets, Kuiper Belt Objects and icy satellites, comets and asteroids, dust, magnetic fields, and plasmas, represents a complex, closely coupled system. Bound by origin, evolution, and interaction, this system not only offers a natural laboratory for understanding a variety of physical, chemical, and magnetospheric processes on bodies throughout the solar system, including the Earth, but also offers a potential analog for studying both astrophysical phenomena and extra-solar planetary processes.

The giant planets represent a key element in tracing the origin, and chemical and dynamical evolution of the solar system. From both the remarkable similarities as well as the striking differences observed in their composition and overall structure, the giant planets provide fundamental clues to the chemical, thermal, and dynamical conditions at the time and location of their formation. In this regard, the giant planets represent time capsules of solar system formation, and, as described by Owen [1], as an ensemble can be considered “a Rosetta stone” for understanding the formation and evolution of the solar system. In particular, the elemental abundances and isotopic ratios found in the well-mixed deeper atmospheres can help discriminate between competing theories of giant planet origin and evolution.

Models of giant planet formation predict that relative to hydrogen, abundances of heavy elements in the outer solar system should be enriched as compared to the solar abundances. Furthermore, these models predict that this enrichment should increase from Jupiter outwards to Neptune. Particularly important are the abundances of noble gases and their isotopes, as well as other heavy elements including carbon, nitrogen, sulfur, and oxygen in the well-mixed deep atmosphere. Methane (CH_4), the primary reservoir of carbon in the outer solar system, is especially important since carbon is the only heavy element so far measured on all the giant planets. The ratio of carbon to hydrogen (C/H) is observed to increase from three times solar at Jupiter to 30x solar or more at Neptune [3]. Theory dictates that the other heavy elements should likewise increase in abundance from Jupiter to Neptune.

Many of the most diagnostic heavy elements are incorporated in volatile species such as water and ammonia that participate in photochemical reactions and haze- and cloud-forming processes in the upper atmosphere. Consequently, it is only in the deep atmosphere well below the condensation clouds that such species are expected to be well-mixed, so that their measured values are then true indicators of their bulk abundances [4]. As temperatures decrease with increasing solar distances, condensation clouds will generally form at greater depths, sequestering the well-mixed atmosphere to deeper levels as well. In the relatively warmer climes of Jupiter, equilibrium models predict an upper cloud of ammonia (NH_3), a second, slightly deeper cloud of ammonium hydrosulfide (NH_4SH), and either (or both) cloud(s) of water ice and water-ammonia mixture. The water cloud is expected to be the deepest cloud deck at Jupiter, with a base predicted to be at depths of 5 to 10 bars depending on values of O/H of 1 to 10 times solar [3]. Thus, measurements of the bulk planetary oxygen abundance require measurements beneath the 10-bar level on Jupiter.

The situation is even more adverse at Saturn. Assuming a heavy element enhancement of 10x solar, equilibrium thermodynamics predict that the deep atmosphere where water will be well-mixed can only be found beneath about 20 bars. Due to dynamical processes (e.g., convection, planetary waves) in the turbulent Saturn atmosphere, the well-mixed region could actually be pushed as deep as 50 to 100 bars in places [3].

In the most distant, colder regions of the solar system, water ice and water-ammonia solution clouds are expected to form at even deeper levels. Thermochemical equilibrium calculations suggest that the base of a Neptune water-ice cloud may be located at 50-100 bars for an O/H ratio of 30-50x solar, and the base of a water droplet (ammonia-water solution) cloud could be as deep as 370 bars and 500 bars, respectively, for O/H of 20-30x and 50x solar [4,5]. In addition, these planets are also expected to have ionic water-ammonia oceans at tens of kilobars which depletes the upper atmosphere of water [4,5]. Designing descent probes to reach and communicate from the deep-mixed levels on these planets is a truly formidable if not intractable problem.

However, given knowledge of the abundances of oxygen and nitrogen in the largest giant planets, Jupiter and Saturn, informative models of the formation of the ice giants, Uranus and Neptune, can be constrained without direct measurements there of the oxygen and nitrogen elemental abundances. Information gleaned on the amount of volatiles delivered to Jupiter and Saturn in the form of ices can then be extrapolated to Uranus and Neptune. Combined with measurements of a host of noble gases and their isotopes, $^{15}N/^{14}N$ and D/H, as well as the inventory of carbon from methane and other hydrocarbons, formation models of Uranus and Neptune can fortunately be meaningfully constrained. For these planets, additional constraints come from measurements of helium and neon [2,3]. These elements cannot be accurately measured in Jupiter and Saturn, because in these gas giants, atmospheric neon is expected to dissolve in helium droplets which then rain into the deep interior, thus depleting the measurable upper atmosphere of both of these elements. Such depletions are not expected to occur in either Uranus or Neptune as helium can not condense within them, and thus their original abundances at formation are preserved. Therefore, with the exception of measurement of oxygen (water) in the deep atmosphere of Saturn, compositional science critical to the understanding of solar system origin and evolution, and giant planet formation, can be obtained from shallow descent probes reaching no deeper than several tens of bars.

The key measurement objectives addressing critical issues of giant planet origin, evolution, and processes are summarized in Table 1.

Table 1.
Outer Planet Probe Measurement Objectives

Primary	
	Abundances of noble gases & isotopes
	Abundances of C, N, O, and S
	Pressure & Temperature structure
Secondary	
	Cloud properties
	Dynamics

To achieve the measurement objectives, a strawman instrument payload based primarily on the Galileo probe is assumed (Table 2).

Table 2.
Nominal Probe Instrument Complement

-	Gas Chromatograph/Mass Spectrometer
-	Atmospheric Structure Inst. (incl 3-axis accelerometry during entry)
-	Nephelometer
-	Doppler Wind
-	Ortho/Para Hydrogen
-	Analog Resistance Ablation Detector (ARAD)

2. MISSION DESIGN

The primary challenges of shallow probe DTE missions include (1) adequate communication link from depth in an absorbing atmosphere, (2) sufficient protection against the thermal heat of entry, and (3) sufficient observing time at depth. The role of the mission designer in entry probe mission communications is to craft a realizable geometry that allows useful communications from the probe to Earth, or to a relay spacecraft, or to whatever mission element is to receive the probe's transmissions. To enable DTE from a probe in a giant planet atmosphere, the mission design must place the probe in a location that is

1. Of sufficient scientific interest to justify the mission;
2. Accessible within technology (or other) constraints;
3. Amenable to communication with Earth.

Giant planets, especially Jupiter and Saturn, have deep gravity wells with significant ramifications for practical entry probe trajectories. With regard to point 2 above, entry probe speeds upon reaching the destination's atmosphere are extremely high, so the need to survive the entry with available technologies imposes a narrow entry corridor with the proper flight path angle with respect to the local horizontal. For a given destination there is a highly restricted set of possible entry sites, largely determined by the direction of the approach V_∞ vector, as shown in Fig. 1 below. A line from the planet's center in the V_∞ direction intersects the planet's reference surface at the *antipode*. For a spherical, non-rotating planet the set of possible entry site loci is a circle on the planet's "surface", centered the antipode with central angle θ as shown. Non-spherical shape and planetary rotation cause minor distortions (a small number of degrees or less) to the circle. Planetary rotation can cause part or most of these to violate entry speed limitations. For instance, Jupiter entry probes are limited to the short arc of the circle within 5-10 degrees of the equator, on the side of the circle that has the probe traveling prograde with respect to Jupiter's rotation.

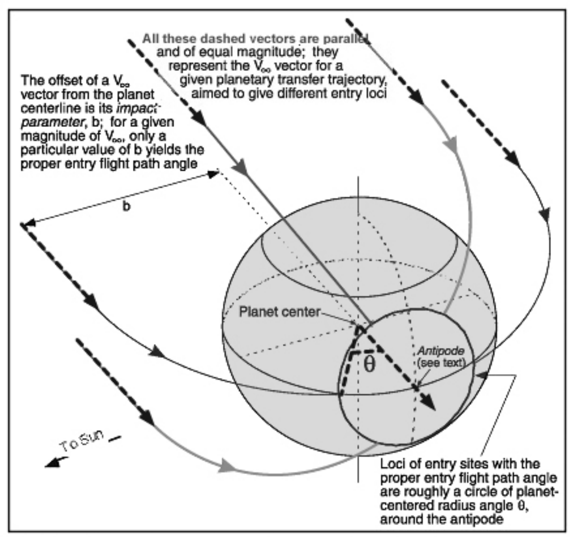


Fig. 1. Entry Trajectories

Without significant propulsive intervention, the transfer trajectory to the destination planet determines the approach V_∞ vector. Using Jupiter as an example as shown in Fig. 2, a tangential (minimum-energy) transfer trajectory to an outer planet yields an approach from the direction the planet is moving: the planet overtakes the slower-moving spacecraft. Angle θ for Jupiter is ~30 degrees (35-37 for Saturn), so the probe enters at a site ~30 degrees sunward of the dusk terminator. After entry the planet rapidly rotates the entry probe past the planet's limb and out of view of Earth, as with the Galileo entry probe. Higher-energy variants of the transfer trajectory can adjust the trajectory-plane components of the V_∞ direction. But the inbound approach that moves the entry point toward the sub-Earth point, advantageous for DTE and "front-side" duration, adds years to the cruise duration to change the entry point longitude by only 20 degrees. Larger adjustments with this method add even more cruise duration, begin to increase the entry speed, and still cannot move the entry point to the sub-Earth longitude. Any significant additional entry location adjustments toward or past the sub-Earth longitude require larger angular rotations available only via propulsive maneuvers.

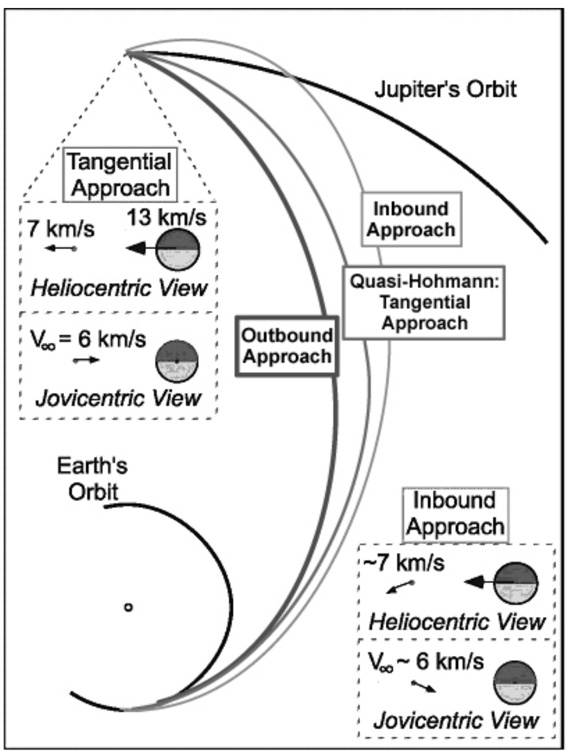
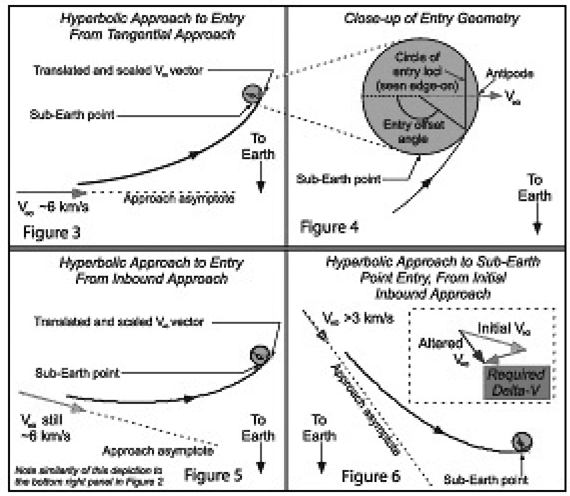


Fig. 2. Jupiter Trajectories

Fig. 3 shows a hyperbolic approach and entry from a tangential transfer trajectory, more nearly to scale than Fig. 1 and looking down on the planet's orbit plane. Fig. 4 is a closer look at the geometry near the planet, showing the Entry Offset Angle, which is the complement of angle θ in Fig. 1 and does not vary significantly with the magnitude of V_∞. This offset angle and the direction of V_∞ determine the Earth-referenced longitude of entry. As the direction of V_∞ changes the entire geometry of Fig. 3 rotates with it. Moving the entry point of Fig. 3 toward the sub-Earth point requires rotating the V_∞ vector clockwise, as seen in Fig. 5, where the 15-degree rotation is accomplished by use of an inbound approach. Further rotation to place the entry site at the sub-Earth point requires an additional 45-degree rotation of V_∞, requiring ~4 km/s of propulsive ΔV (Fig. 6). Greater rotation, necessary if the probe is to be near the sub-Earth point at the end of its mission, requires even larger ΔV.



Figs. 3-6. Entry Trajectory Details

3. COMMUNICATIONS

In this section, the end-to-end communication link analyses from Saturn and Neptune probes to a ground-based receiving station on Earth are discussed.

The primary challenges of a non-coherent DTE downlink from a shallow descent probe are the losses due to antenna mis-pointing, atmospheric attenuation, and free-space propagation. Reliable signal detection requires 1) optimization of the probe communication subsystem to allow for maximum transmitted power, and 2) selection of the Earth station with the required antenna size and the desired pointing capabilities.

To further illustrate these challenges, an end-to-end analysis for both Saturn and Neptune descent probes is presented. A design similar to the Galileo probe is assumed with the exception of increasing the probe's transmitter peak power to 100 Watts. This is consistent with the recent improvements in solid state design and the increase in the overall efficiency of the power transmitter to the 50% mark. Using the Galileo probe as a baseline for the link analysis enables the evaluation and comparison of link budgets using variable antenna diameters on the ground while keeping the probe telecommunications parameters at fixed values.

At 30 AU range from Earth, a signal from a Neptune probe propagates through space and suffers very large space losses, posing serious design challenges for DTE communications. A preliminary end-to-end analysis was conducted, including (1) arraying a single 70-meter diameter DSN antenna with two 34-meter diameter DSN antennas, and (2) utilization of non-DSN space antennas such as Arecibo with its 200 meter diameter. In each case it was found to be impossible to close the communications link at the required 128 bps data rate.

Table 3
Saturn and Neptune Probe

Transmitter Power	100 W
Peak Antenna Gain	9.8 dBi
Antenna Pointing Loss	6 dB

The remaining option was to consider the proposed Square Kilometer Array (SKA). Although still in its conceptual phase, when and if the SKA is implemented it could offer promising enhanced downlink signal gain capabilities. The current SKA design calls for large arrays comprising many small 12 m diameter reflector antennas. A total of 4400 proposed antennas will be combined to meet the required specifications and offer an enormous collecting area with an equivalent 800 meter antenna diameter.

With the much needed help from unparalleled SKA antennas, the issue of a probe antenna's mis-pointing during the descent phase can be addressed. Disturbances in the probe's attitude must be carefully considered in order to satisfy the objective of establishing preliminary bounds on the antenna beamwidth requirement necessary to support the entire critical descent period. The antenna beamwidth must accommodate the following considerations:

(1) Entry and initial link lock from a location significantly removed from the sub-Earth point;
(2) Planetary rotation that might carry the probe even farther from the sub-Earth point;
(3) Perturbations of the probe's spin axis away from the local vertical by such phenomena as aerodynamic buffeting and atmospheric turbulence, each tending to induce pendulum-style swinging, and the possible parachute flow instabilities.

Designing the link with a smaller antenna beamwidth (higher probe antenna gain) may result in serious signal detection outages and possibly even total loss of the science data. In the case of Saturn and Neptune probes, a 6 dB pointing loss equivalent to a beamwidth of 56 deg has been assumed for all link calculations.

The DTE link budget analyses for Saturn and Neptune probes were performed under the assumptions presented in Tables 3, 4, and 5. All parameters of the link budget were carefully selected in order to meet the required 128 b/s data rates. To optimize the link and ensure sufficient margins, different modulation and coding schemes were also explored. The summary of these computed margins is listed in Table 6 and should make it apparent that predicting the link performance of missions utilizing Direct to Earth communication strategies is a complex problem.

Table 4
DTE Link Assumptions

UHF Communications Band	401 MHz
Information Bit Rate	128 bps
Bit Error Rate	1.00e-5
Saturn Distance from Earth	9 AU
Neptune Distance from Earth	29 AU

For the case of a Neptune probe, many computations were carried out to determine the most suitable modulation and coding schemes capable of providing the optimal signal-to-noise ratio at the desired 128 b/s science data rate. Even under the best case link conditions (nominal noise temperature and SEP angles), all computations led to a DTE links with no margin or very poor margin. The case of the residual carrier with concatenated convolutional and Reed-Solomon codes still yielded a margin below the minimum DSN requirement of 3 dB above the threshold SNR needed for proper signal detection and data demodulation.

Table 5

Square Kilometer Array (SKA)	
Ground Antenna Elevation Angle	20º
SKA Collecting Area Diameter	800 m
Receiver Operating Temperature	25 K
Total Noise Temperature	45 K
Threshold Loop Noise BW (Blo)	10 Hz
Required Suppressed Carrier (BPSK) Threshold SNR in Blo	17 dB
Required Residual Carrier Threshold SNR in Blo	12 dB

The analysis is quite different for a Saturn mission. At a spacecraft-Earth range of 9 AU, the corresponding space losses for a Saturn DTE link are reduced by an order of 10 dB compared to the space losses for Neptune's missions. With margins above the 3 dB threshold, a Saturn DTE communications link performance is supportable at 128 bps data rate for atmospheric pressure levels no deeper than 20 bars. However, with its large scale height, presents new challenges as the need to descend deeper than 20 bars will result in significantly higher signal attenuation.

Table 6.
Direct to Earth Communications from Saturn & Neptune Probes
Assuming a Square Kilometer Array (Diameter=800 m)

Atmospheric Pressure			**2 Bars**	**5 Bars**	**10 Bars**	**20 Bars**
Saturn's Atmospheric Attenuation (dB)			**0.12**	**0.71**	**2.03**	**5.46**
Neptune's Atmospheric Attenuation (dB)			**4.63E-06**	**4.06E-04**	**9.48E-03**	**1.368**
Suppressed Carrier (BPSK) Conv (rate=1/2) MI = 1.57 (Rad/pk)	**Saturn**	Data Margin (dB)	11.44	10.85	9.52	6.02
	Neptune	Data Margin (dB)	**No_TLM**	**No_TLM**	**No_TLM**	**No_TLM**
Residual Carrier Turbo (rate=1/6) Blk Size 8920 MI = 0.9 (Rad/pk)	**Saturn**	Carrier Margin (dB)	11.46	10.87	9.55	6.12
		Data Margin (dB)	13.75	13.15	11.83	8.34
	Neptune	Carrier Margin (dB)	**No_Lock**	**No_Lock**	**No_Lock**	**No_Lock**
		Data Margin (dB)	**No_TLM**	**No_TLM**	**No_TLM**	**No_TLM**
Residual Carrier Conv (rate=1/6) + R/S (223/255) MI = 0.8 (Rad/pk)	**Saturn**	Carrier Margin (dB)	12.45	11.86	10.54	7.11
		Data Margin (dB)	12.29	11.7	10.37	6.91
	Neptune	Carrier Margin (dB)	2.44	2.44	2.43	1.07
		Data Margin (dB)	2.13	2.13	2.12	0.69

4. TECHNOLOGY ISSUES

The technology development challenges in designing, producing and testing a DTE probe are numerous. Certainly, the most difficult of these is the thermal design. To allow the carrier spacecraft to perform a deflection maneuver and avoid following the probe entry trajectory, a typical probe mission plan schedules probe separation from the carrier spacecraft some period of time before actual planetary entry,. The probe coast period can be anywhere from several weeks (e.g. 3 weeks for Huygens) to several months(e.g., 5 months for Galileo). During this time period, there is extremely low power dissipation within the probe to preserve battery life, and the thermal design for this mission phase must maintain the probe instrumentation, including sensors, electronics and mechanisms, above their thermal design limit.

Shortly before the probe enters the planetary atmosphere, the high power transmitter is turned on, dissipating substantial thermal energy. In addition, the probe deceleration generates external heat. These two factors drive the thermal design to maintain the probe elements below their upper thermal limits. Early probes used passive thermal blankets and high molecular weight gas to maintain hardware temperatures within acceptance ranges. Current probes have other techniques available for thermal control. Phase change materials, Aerogel and complex thermal blanket designs are other techniques used to implement the probe thermal design.

Batteries remain the only practical means of powering a probe following separation from the carrier spacecraft. Although nuclear sources and other techniques have been considered, probe mass limitations dictate the use of a compact battery. Recent planetary entry probes, including the Galileo and Huygens probes, used $LiSO_2$ batteries. This technology remains the most reliable and efficient probe battery chemistry. These batteries are characterized by extremely low self discharge levels and remain stable over the long duration mission phase between launch and first use just prior to probe separation.

Although the probe transmitter will certainly require the highest energy, evolving improvements in solid state designs can increase transmitter efficiency from 30% used in the TWTs on the Pioneer Venus and Galileo probes, to levels approaching 50% even at UHF bands. Low powered logic and power conditioning circuitry electronics minimize power draw from other housekeeping functions. Instrumentation power consumption too has benefited from circuitry improvements, miniaturization, and technology investment.

The probe telecommunications subsystem must also include an ultra stable oscillator (USO), to improve transmission quality and serve as the main part of a Doppler wind measurement. Inclusion of a transponder, although desirable to measure descent profiles and provide a coherent signal, may not be possible due to power and mass budgets. Descent dynamics and aerodynamic forces are a big driver to antenna design and may limit physical size

The deceleration module design is critical to protect the sensitive instrumentation from the intense entry heat. Its mass fraction, as a percentage of the total probe separated mass, can be considerable, depending on the probe entry trajectory and planetary atmosphere. Table 3 summarizes deceleration mass fraction of recent planetary entry probes. The deceleration module separation system, required to allow instrumentation to sample and image planetary atmospheres for instrument access to planetary atmosphere, also adds to the deceleration module mass.

Table 7

Probe Deceleration Module Mass Fractions

Probe Mission	Mass Fraction (%)
Pioneer Venus	36
Galileo	63
Huygens	33

The heat shield thermal protection subsystem (TPS) design is critical to maintaining sensitive electronics within the probe below their thermal limits. An ablative design is optimal. Although fully dense carbon phenolic was the historic material used on Pioneer Venus and Galileo probes, it is no longer manufactured. However, TPS designs for entry probe descent missions may not require the use of the historic carbon phenolic material and can make use of other ablative materials, such as pica.

5. SUMMARY AND CONCLUSIONS

For Direct-to-Earth communications to be viable, the Earth must be in view of the probe throughout the period of the communication link. In most practical cases this limits the probe atmospheric entry to the west (retrograde or approaching) limb of the planet, with the probe trajectory swept across the sub-Earth meridian by the planet's rotation. Although a prograde entry on the west limb of the planet is certainly possible, prograde entries generally require a significant increase in ΔV and overall mission duration. Retrograde probe entries are more easily realized, but can severely impact the mission design, as well as thermal protection systems and, in consequence, total probe mass. Missions with multiple entry probes are even more severely constrained by the requirement of west-limb entry.

When a mission design relies on a DTE telecomm strategy, a number of other issues must be considered including: (1) increased probe transmitter power necessary to overcome the large initial probe-to-Earth aspect angle (due to the vertical descent of the probe near the west limb of the planet) resulting in lower off-axis gain; (2) proper phasing of the probe delivery with the Earth rotation such that the proper Earth-based antenna system(s) is (are) able to view the entire probe descent; (3) consideration of single point failure risks arising from an unfortunately timed occurrence of adverse weather or technical issues with the Earth antenna systems; (4) design of a communications link able to provide a data rate suitable to support the probe instrument payload and mission science floor; (5) limiting descent time to reach the target depth within the Earth visibility window; and (6) accommodating the TPS mass fraction needed to survive the entry conditions. In most practical cases this will be a retrograde entry.

Although the telecommunications aspect of the DTE technique is indeed challenging, the most critical issues are those associated with mission design and technology – delivering a probe to the approaching limb of a planet will generally require a retrograde entry, significantly increasing the TPS mass fraction. To complete a descent probe mission to a minimum depth defined by the science floor within the time constraints imposed by Earth visibility and the rotational period of the planet requires a rapid descent. For Saturn, with a large atmospheric scale height, an entry probe mission may need to be conducted without a parachute. Perhaps the most challenging aspect of an outer solar system DTE mission is the development of a system of Earth antennas capable of closing the link without the potential of a single point ground failure jeopardizing the science return. If an array of spatially-separated Earth antennas can be developed to maintain probe visibility throughout the descent, this issue will be largely alleviated. Unfortunately, such a system is not envisioned in the near future.

The Galileo and Huygens missions have demonstrated the viability and value of Direct to Earth communications for an outer planet descent probe mission. Indeed, the Huygens Doppler Wind measurement could not have been completed without DTE communications, this technique should be included as an important consideration in the design of future missions. A specific investigation that will continue to benefit from DTE is measurement of deep atmosphere dynamics by Doppler tracking of descent probes. Coupled with a probe-to-relay spacecraft communications link, the probe-to-Earth link provides a second Doppler component that allows the retrieval of a 2-dimensional wind vector.

Direct to Earth communications is a proven technique that should be maintained in mission planning, may be utilized in the definition of future outer planetary missions, and will continue to provide unique science opportunities. However, overall risk, mission and telecommunications link design, and current TPS technologies are challenges that must be carefully weighed in designing missions that rely on DTE communications link as the only means of returning the entry probe data.

REFERENCES

1. Owen, T. "Atmospheric Probes: Needs and Prospects," *Proceedings of the International. Workshop, Planetary Probe Atmospheric Entry and Descent Trajectory Analysis and Science, Lisbon, Portugal, 6-9 October 2003*, ESA SP-544, February 2004, pp. 7-12.

2. Atreya, S.K, Bolton, S., Guillot, T, Owen, T.C., "Multiprobe Exploration of the Giant Planets – Shallow Probes," 3rd International Planetary Probe Workshop Proceedings, NASA/ESA Special Publication, 2006 in press.

3. Atreya, S.K., et al., "A Comparison of the Atmospheres of Jupiter and Saturn: Deep Atmospheric Composition, Cloud Structure, Vertical Mixing, and Origin," *Planetary Space Science*, 47, 1999, pp. 1243-1262.

4. Atreya, S.K, "SATURN PROBES: Why, Where, How?" 4th International Planetary Probe Workshop Proceedings, NASA/ESA Special Publication, 2006 in press.

5. Atreya, S.K. and Wong, A.S. "Coupled Clouds and Chemistry of the Giant Planets - A Case for Multiprobes," *Outer Planets* (R. Kallenbach, ed.) Kluwer Academic, 2004